HOLOGRAPHY

Revised 16 May 2005.

When a hologram is made, a coherent beam of light is divided so that one beam (the reference beam) falls directly onto a piece of photographic film and another beam (the object beam) is formed from the light that is scattered by an object and falls onto the same piece of film. When the two beams are recombined in this way, they make an interference pattern which is recorded on the film. If the film is illuminated with coherent light, the light will be diffracted as if by a diffraction grating, giving rise to a diffraction pattern containing the zeroth and first orders. The first order reproduces the full wavefront of the light scattered from the original object and gives a 3D virtual image of the object for the light transmitted through the film and a 3D real image for the light reflected from the film. The purpose of this experiment is to investigate the properties of holograms by 1) making a transmission hologram of actual objects and observing its optical characteristics, and 2) making a diffraction grating by combining two beams of light in order to examine the holographic process in its simplest form.

REFERENCES

1. Lipson, *Optical Physics* (3rd ed.), pp. 363-370.
2. M. Françon, *Holography*, pp. 17-23, 29-36. (especially for understanding the diffraction grating)
3. M. Parker Givens, "Introduction to Holography," Am. J. Phys. **35**, 1056 (1967).
4. J. E. Kasper and S. A. Feller, *The Complete Book of Holograms: How they work and how to make them*.
5. Hecht, *Optics* (4th ed.), pp. 623–639, holography; pp. 606–609, sine-wave gratings.
6. Response of photographic film, Appendix to this write-up.

SPLIT-BEAM TRANSMISSION HOLOGRAM

SETTING UP THE OPTICS

The general layout for making the hologram is shown in Fig. 1. The shutter is on a floor stand so that, when it is opened, vibrations are not transmitted to the table top. The shutter is activated by a DC power supply connected to an enlarger timer; both of these are underneath the table, as is the laser power supply. To keep the shutter open during set-up, flip the FOCUS/TIME switch on the shutter controller to the FOCUS position. If the shutter does not open, check that the shutter power supply is turned on and that the voltage is set to 12V.

After the laser beam passes through the shutter, it is split into two *object beams* and one *reference beam*. The mirrors and microscope objectives are interchangeable. However, the beam splitters are *not identical*; they should be placed according to their labels, with the laser beam hitting the mirrored side first.

Start by centering the film holder near the end of the table across from the laser. Put the stand 6 to 8 inches from the film holder, and then put the tall dark screen directly behind the stand. Place your objects near the center of the stand so that they are easily viewed through the film holder. You will get more interesting results if you arrange the objects to emphasize the three-dimensionality of the holographic image: let one object partially occlude the other, or place a lens so that you can see one part magnified as you move your head from side to side. Use your imagination! Hint: the brightest holograms are made from objects which reflect the light strongly but diffusely, like the silver painted chess pieces.

As with several other experiments in the 331 lab, the optics in this experiment are centered 6" above the table top. It is helpful to keep all the beams at or near this level. Beam height can be easily checked with the 4"×6" index cards available in the lab.

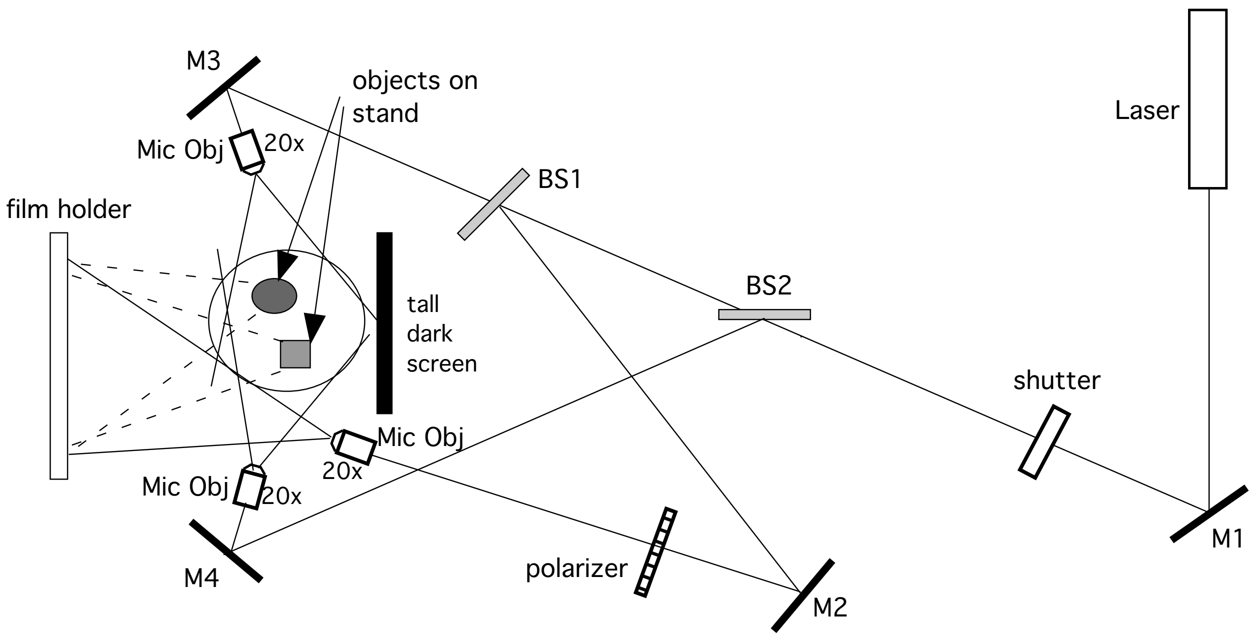

Figure 1: Setup for hologram exposure.

Position mirrors M3 and M4 equidistant (about 8") to the left and right of the film holder, and orient them so that they roughly face a point at the center of the object stand. Place mirror M1 in the laser beam path and direct the beam through the shutter and diagonally across the table to mirror M3. Make sure that the beam passes through the center of the shutter opening. Now place beamsplitter BS2 in the beam path about 1/3 of the distance from M1 to M3 so as to split off part of the beam to mirror M4. Leave about 1 foot between the shutter and BS2 to permit later viewing of holograms with collimated laser light. Place BS1 beyond BS2 in the beam path. Position M2 as shown in Fig. 1 and orient M2 so that the beam reflected from it hits the center of a white card placed in the film holder, making an angle of 25 to 30 degrees with the normal to the film holder. Adjust mirrors M3 and M4 so that both beams hit the objects.

IMPORTANT: Experience has shown that in order to get a good hologram (or any image at all!), the distance traveled by all beams to the film plane *must be the same* to within a centimeter or two. Thus, the total distance BS2 $\rightarrow$ M3 $\rightarrow$ objects $\rightarrow$ film must be the same as the total distance BS2 $\rightarrow$ M4 $\rightarrow$ objects $\rightarrow$ film, and these distances must be the same as BS2 $\rightarrow$ BS1 $\rightarrow$ M2 $\rightarrow$ film. The easiest way to make the distances the same is to use the symmetry of the object beam paths to equalize them, measure the distances with a tape measure, and then adjust BS1 and M2 to make the reference beam path equal the object beam paths.

Microscope objectives are used to diverge the laser beam. Place the three objectives as shown in Fig. 1. Adjust the reference beam objective so this beam illuminates the white card in the film holder as *evenly* as possible; if you see the "edges" of the beam spot on the white card, the objective is too close to the film holder. Now cover M2 with a beam blocking card.

Caution: you will be viewing parts of this experiment with your eyes at the same level as the laser beam. Make sure that the direct, undiverged laser beam never shines directly into your eye, as this may cause permanent eye damage.

Adjust the M3 and M4 objectives to optimize the illumination of the objects on the stand. Remove the white card and look through the film holder to determine the object positioning which will give the best perception of depth as you move your eye around while looking through the film holder. If you move the objects, re-optimize their illumination by adjusting M3 and M4, and then the corresponding objectives.

Now you need to set the "beam balance": the relative intensity of the light from the object beams to the light from the reference beam. Place the polarizer in the reference beam path, and adjust its orientation so that the reference beam is brightest. Remove the white card from the holder (if it's still there), and place the front part of the photodetector assembly so that the ground-glass window is in the film plane. Connect the photodetector to the PDA-700 current amplifier, turn it on, and set it to the microamp range (μA). Turn off all of the lights in the room (except the green safelights), and close the door. With the beam shutter closed, set the "offset" of the PDA-700 so that it reads zero.

Open the shutter. You should see the reading go to around -0.02 to -0.05 μA with all beams on. Now cover M2 to block the reference beam and measure the light coming off of the objects. This is typically about -0.005 μA, but don't worry if your value is a little different. Then cover mirrors M3 and M4, and uncover mirror M2. Adjust the polarizer angle to make the reference beam intensity about a factor of 4 greater than what you measured from the object beams. For example, if you measured -0.005 μA from the object beams, set the polarizer to give an intensity of -0.020 μA from the reference beam. Now remove all of the beam blockers and measure the total light intensity.

If you have measured a total intensity of about -0.025 μA, choose an exposure time of 20 seconds; if your light is significantly different from this (say, a factor of 2), adjust your exposure time accordingly, keeping the exposure time $\times$ light intensity equal to a constant. Set the controller to open for the desired time. The dial on the left is in increments of 10 seconds, while the dial on the right is in 1 second increments (with x1/x10 switch in x10 position). Exposure time can be adjusted as needed if your first hologram is underexposed (film very light before bleaching) or overexposed (film *very* dark before bleaching). As explained in the Appendix on photographic film response, you should try changing your exposure time by factors of 2 if you don't get a good hologram at first.

Remove the photodetector assembly from the table and turn the PDA-700 off. Make sure that the hardware supporting the shutter is not contacting the optics table and flip the FOCUS switch to close the shutter. Any contact with the table will introduce vibrations when the shutter is opened, and thus prevent you from achieving a good hologram.

EXPOSING AND DEVELOPING THE FILM

Prepare the trays of developing chemicals. Fill all trays to a depth of about 1 cm. Fill the large glass dish in the sink with water for washing purposes. Learn how the timer by the chemicals works. You will need to time the developing steps in the dark. The developing procedure is as shown below.

Developer	Stop bath	Fixer w/o Hardener	WASH (sink)	Transmission Bleach	WASH (sink)	Photo-Flo (hand)
$\approx$ 3 minutes	30 sec	2 minutes	1 minute	(until clear)	1 minute	

NOTE!! RINSE IN WATER IN SINK TRAY 1 MINUTE BEFORE AND AFTER BLEACH

Before turning out the lights, **please go over the three-piece, light-tight example film box (no film inside!) to be sure you understand how it goes together**. The film we use is a special Agfa holographic film with an "antihalation coating". It is placed in batches of a few pieces in a light-tight box. **Do not discard the film box when you are done—it will be refilled and used again**.

IMPORTANT: In order for a distinct pattern of interference fringes to be recorded, it is necessary to limit the movement of the objects, film and optical components to less than a wavelength of light during exposure. For this reason, *care must be taken to minimize any perturbations of the system while the film is being exposed.*

Turn off all lights in the room (except green lights) and close the shutter (flip FOCUS/TIME switch to TIME). Remove a piece of film from the film storage box and put the covers back on the box. Place the film in the film holder so that the concave side (emulsion side) is facing the object. *IMPORTANT:* after loading the film, stay in one place near the shutter controller for 15-20 seconds and let the film relax. Trigger the shutter (push the large white button on the right) for the set exposure time and do not move, talk, or make any noise at all while the shutter is open. After exposing, remove the film and develop.

Put the film in the trays with emulsion side up. **Use gloves and tongs to avoid chemical interaction with your skin. The transmission bleach is caustic and can stain your clothes—wear a lab coat too.** The film should be rinsed well in water before and after bleaching. It is a good idea to rock the trays gently while developing, so the film develops evenly. After the fixer step the room lights can safely be turned on. (Before turning on the lights, check that the covers are back on the film storage box.) When finished with the last wash of the film, hold the film by one edge with a darkroom clip and thoroughly rinse both sides of the film with the squirt bottle of photo-flo solution. Then dry the film by waving it in the air. Avoid touching the emulsion side of the film until it is dry.

VIEWING THE HOLOGRAM

While the hologram is still wet, hold it up so that you see the ceiling lights through it; you should see a silvery shimmer caused by light scattering off of the very fine diffraction pattern. If you see only a clear darker region, or just a clear piece of film, chances are you have failed to make a good hologram.

If you have a good hologram, view it in the following ways. **NOTE: These observations will be required for your report, so you will want to come back to them and record carefully what you see.**

After the hologram has dried, try viewing the image projected onto a white card by placing the film just after the shutter, and by holding an index card 6 inches or so beyond the film. You should see two images, depending on the orientation of the film: one will be right side up and the other will be inverted. Try different angles between the laser beam and your film, as well as different spots on the film.

Next, view it by placing it back in the film holder with the curved side towards the laser. Illuminate the hologram by letting the reference beam shine through it. To make sure you are seeing an image from the hologram, block the light from the objects with a dark card while making sure not to block the reference beam. Look at the hologram from different points of view and notice how the scene varies.

Try turning the film upside down with emulsion side still towards the laser to look for a pseudoscopic image. It will appear odd, as if you are looking through a magnifying glass.

HOLOGRAPHIC DIFFRACTION GRATING

To make the diffraction grating, reconfigure the optics as shown in Fig. 2, leaving the two microscope objectives out for the time being. For this set up, the film holder should be in about 10” from the edge of the table. Adjust M4 so that the beam makes an angle of about 15 degrees with the normal to the film holder. Adjust BS1 and M2 so that the beam from M2 also makes an angle of about 15 degrees with the normal to the film holder.

HINT: Use a clear plastic protractor held against the film holder to see the pencil of light as it impinges on the holder. This will allow you to set the angles accurately.

Put an objective beyond M4 to diverge the beam and evenly illuminate a white card in the film holder. Do the same for the beam from M2, making sure that the two objectives are an equal distance from the film. Measure the distances from the center of the film to the near end of the microscope objectives (taking care not to touch the glass surfaces!) and measure the distance between the ends of the two objectives. Compare the intensities of the two beams and use a polarizer between BS1 and M3, or between M2 and its objective if needed, to equalize the intensities of the beams.

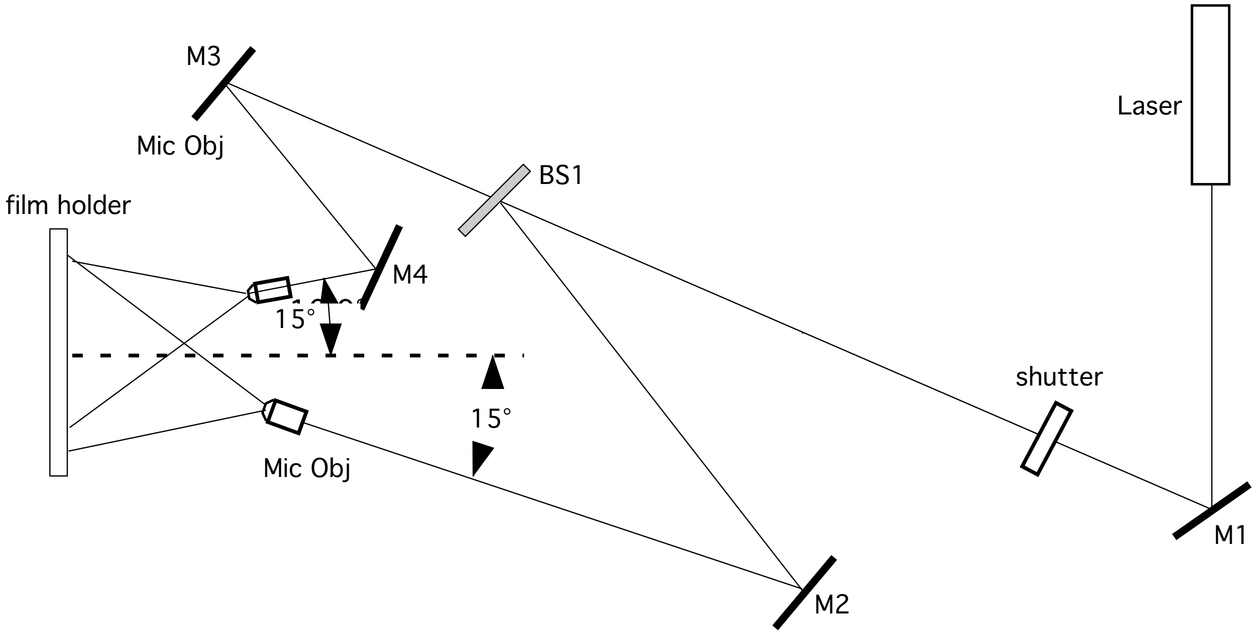

Figure 2: Setup for diffraction grating exposure.

It is possible to view the fringes that fill the space where the two beams overlap. Without disturbing the film holder, position the microscope (consisting of just a tube, eyepiece and objective) so that the end of its objective is at the film plane. You should be able to observe the finely-spaced vertical fringes and notice how they disappear momentarily when the table is tapped or when one of the beams is blocked off. If you don't see these fringes, there may be a problem with the relative beam intensities or some other misalignment.

Since the beams illuminate the film directly, the exposure time is much shorter than for the hologram. Start with an exposure time of 3 to 5 seconds and then adjust the exposure time as needed. Develop the diffraction grating using the same procedure as with the hologram.

After you have bleached the film, view the ceiling lights through it. If you have made a good exposure, you will see a brilliant shimmer along with a bright rainbow off to one side. If you have overexposed the film, you may see the diffraction effect around the edges of the film but not in the center.

See the section "Required for your report" for further observation instructions.

CLEAN UP

When you are finished in the darkroom, cover all of the trays with their covers, and use a damp sponge to wipe up any spills and drops from the chemicals. The lab management will take care of any chemical disposal and replacement.

Cover all of the optics with the dust covers.

Turn off the laser and shutter controls.

REQUIRED FOR YOUR REPORT

1. Each team must turn in at least one transmission hologram of an object or objects of their choice and one diffraction grating, both made by your team. These will be viewed by the laboratory assistant grading the report, so be sure to label your holograms and explain how to view them. You must make a diagram labeling the placement and kind of objects used for the transmission hologram, and note the exposure times for each hologram with labels on the edge of your film.

2. Describe the necessary components for making a hologram.

3. Each individual must describe the following observations made while viewing the transmission hologram of an object:

   (a) Describe your observations of the hologram under these conditions, as detailed above: (i) the images made by projecting the unspread beam through the hologram onto a screen, (ii) the image viewed by looking through the hologram illuminated by the (spread) reference beam, and (iii) the pseudoscopic image you see when you flip the hologram over.

   (b) Under viewing condition (ii) above, what does covering up part of the hologram do to the image you see?

4. Each individual must describe the following observations made with the diffraction grating:

   (a) View the effect of the diffraction grating on the laser beam by placing it just beyond the shutter and looking at the image on a white card. Vary the angle between the laser beam and the hologram and observe the spots produced. When the diffraction spots are equally spaced on either side of the central spot, measure the angle between the zero and first orders and compare that with what you expect from the geometry used in creating the hologram.

   (b) Look through the hologram at a concentrated source of white light and describe what you see. Try looking at both incandescent and fluorescent light sources.

   (c) In what way is your diffraction grating similar to and different from the sine wave grating discussed in Section 13.2.1 of Hecht (4th ed., pp. 606–609)?

5. Discuss the differences between your transmission hologram and your diffraction grating.

6. What are some differences between a hologram and an ordinary photograph?

APPENDIX: RESPONSE OF PHOTOGRAPHIC FILM

In order to do the holography experiment it is important to understand how photographic film responds to light. Photographic film has a limited range over which it can accurately distinguish contrast in a scene, a range which is less than that of your eye.

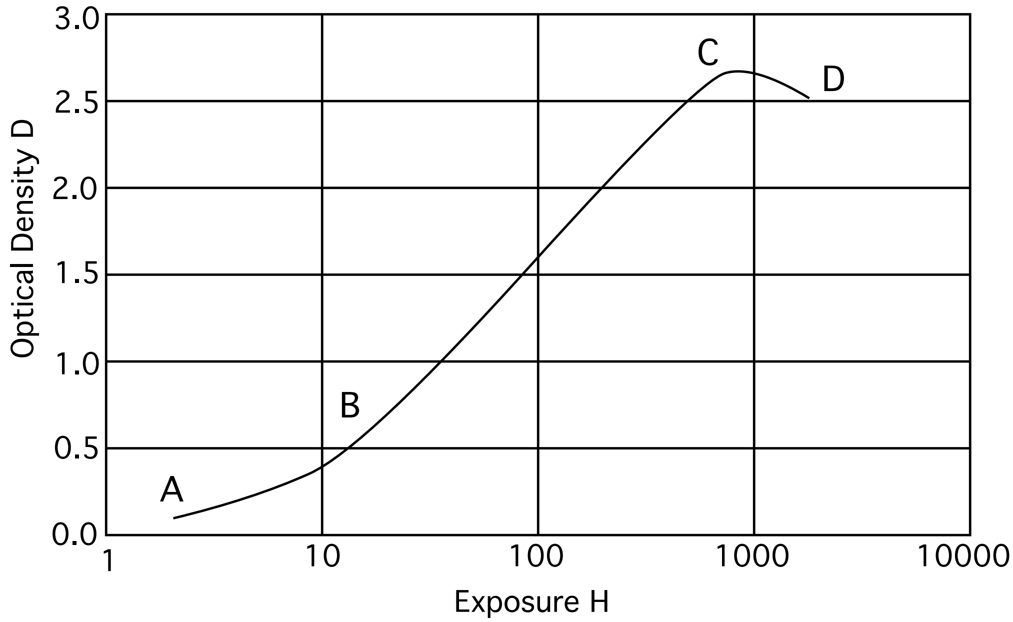

Figure 3: Film response curve.

All photographic film has what is known as a Characteristic Response Curve. This curve is plotted in terms of the optical density of the negative D versus the logarithm of the exposure H. For a negative film the optical density is defined as the logarithm of the inverse of its transmittance:

$$D = \log \frac{1}{T}$$

where T is the ratio of the intensity of light transmitted through the negative to the intensity of light incident on the negative. (Hence, the less light transmitted by a negative, the greater its optical density.) The exposure H is essentially the energy received by the emulsion:

$$H = Et$$

where E is the illuminance (watts/m^2/s) incident on the emulsion and t is the exposure time.

The characteristic curve of a film is based on empirical data; the basic shape of the characteristic curve is the same for all photographic film. (See Fig. 3). In the regions between points A and B, and between points C and D, changes in the exposure, H, produce little or no changes in the optical density of the negative and, hence, little or no contrast. Within the region between A and B, a photograph is said to be underexposed (appearing dark or black). Between C and D, the photograph is said to be overexposed (appearing bright or bleached). It is within the "linear" region, between points B and C, that one wishes to be working in order to obtain greatest range of detail in a photograph.

Within the linear region of a film's characteristic response curve, you can obtain good photographs under varying light conditions. This is done by controlling the exposure time and the amount of light incident on the film. For those of you familiar with 35 mm cameras, exposure time and the amount of light are controlled by the shutter speed and f-stop setting on the camera. The f-number (denoted as $f/\#$) is defined to be the ratio of the focal length of the lens to the diameter of the aperture on front of the lens:

$$f/\# = f/D \ ,$$

where f is the focal length and D is the diameter of the limiting aperture.

The incident light flux is proportional to the area of the limiting aperture. Therefore a change in the aperture diameter by factors of $\sqrt{2}$ changes the incident flux by factors of 2. The same change in incident flux can be achieved by keeping the diameter constant and changing the exposure time by factors of two. In our experiments, light intensity can be reduced by using a Polaroid filter (There are no f-stops) and the exposure time is determined by the shutter controller. For those of you interested in further investigations of photography and the properties of photographic film, the following sources are recommended:

1. Françon, M., *Holography.* (Academic Press, NY, 1974), pp. 20–23.

2. Williamson, Samuel J., *Light and Color in Nature and Art*, (Wiley, NY, 1983), pp. 467–474